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JPL PUBLICATION 77-51, VOLUME VI

Report of the Terrestrial Bodies Science Working Group Volume VI. The Asteroids

(NASA-CR-155184) REPORT OF THE TERRESTRIAL
BODIES SCIENCE WORKING GROUP. VOLUME 6:
THE ASTEROIDS (Jet Propulsion Lab.) 19 p
HC A02/MF A01

CSCL 03B

N77-34079

Unclas

G3/91 50482

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OVERLEAF: Asteroids—A Myriad Diversity

Asteroids represent a difficult challenge to exploration: thousands upon thousands of bodies scattered throughout the solar system, each following a singular path, divorced in space and time from its many "companions." In this figure, the Earth-orbit-crossing asteroid Eros is seen in an artist's rendition of its close approach to the Earth—Moon system (seen within the coronal glare of the Sun).

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Volume VI. The Asteroids

September 15, 1977

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PREFACE

This volume is one of a nine-volume series documenting the work of the NASA-sponsored Terrestrial Bodies Science Working Group in developing plans for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets during the period 1980-1990. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

This volume is the report of the asteroids subgroup, whose members and contributors are C. R. Chapman (chairman), T. V. Johnson, and T. B. McCord.

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SECTION I

INTRODUCTION

Of all potential targets for space missions during the 1980's under consideration by TBSWG, the asteroids are those for which mission profiles are least well-defined. There are special problems in the exploration of this group of bodies; each one is smaller than any body previously studied by spacecraft and they are widely distributed throughout an immense volume of space. Encounter durations are extremely brief compared with travel times between successive bodies in a multiple-asteroid flyby mission. Low-thrust propulsion systems offer possibilities of longer staytimes, but no mission analyses of these options have yet been undertaken.

SECTION II

RESULTS OF PREVIOUS EXPLORATION

All we have learned about the asteroids has been from ground-based astronomical observations and, indirectly, from laboratory analyses of meteorites. In some sense, the ground-based and laboratory studies of the past decade have constituted the "reconnaissance" phase of NASA's asteroid exploration program. More than 300 asteroids have at least crudely known physical properties (e.g., colors, albedos, rotation rates). The best observed objects have "known" major mineralogies (e.g., Fe/Mg ratio in pyroxenes or olivines, percentage of opaques, percentage nickel-iron). The compositional distributions as a function of diameter, semimajor axis, Hirayama family membership, rotation periods and other parameters have been studied. Reconnaissance observations are continuing and more detailed astronomical techniques are being applied to some particular objects; these techniques include mid-infrared spectroscopy, radar backscatter, and photometric astrometry.

SECTION III

SCIENCE OBJECTIVES: BACKGROUND

The asteroids are a population of bodies of 1000-km diameter and smaller that orbit the Sun in modestly inclined and eccentric orbits between the orbits of Earth and Jupiter, concentrated between 2 and 4 AU. Asteroids may be remnants of a planet that failed to accrete in the belt; unlike comets, they probably orbit at roughly the distance from the Sun at which they formed. Ground-based observations indicate that they are highly varied in mineralogical composition and other properties. Some are apparently the parent-bodies for most meteorites. Over 90% of asteroids seem to be of geochemically primitive, carbonaceous composition, while some of the larger ones show evidence of considerable thermal evolution (differentiation and perhaps crust and core formation). Colliding asteroids may have revealed their interior rocks and given rise to fragments that have rained down on planets as meteorites and crater-forming projectiles.

As the only population of minimally altered remnants from the accretional phase of solar system history which remain in roughly their original orbits, the asteroids offer unique clues to the first half-billion years of planetary evolution. By placing the meteorites in their asteroidal context, we can maximize the benefits from such "free" extra-terrestrial samples. We do not know which asteroids are the meteorite parent-bodies, but studies suggest that the meteorites are not a representative sampling of asteroidal material.

In more detail, asteroids have the following traits

- (1) Most but not all asteroids are thought to be of primordial composition. They have suffered a minimum of chemical and physical alteration since they probably never grew to sizes much larger than 1000-km diameter and probably have not been heated to more than a few hundred degrees K. Thus they probably preserve compositions, textures, layers, and other features from the time they accreted. Indeed asteroids may be fragments of actual planetesimals like those from which planets accreted. Some (e.g., Trojans) may not even be fragmented.
- (2) Asteroids, unlike comets, are believed to be in roughly their original orbits (e.g., to within a few tenths of an AU in semimajor axis). Thus their primitive characteristics may be related to specific parts of the condensing and accreting planetary nebula.
- (3) For at least the past 4 billion years asteroids have been undergoing net fragmentation and erosion by collisions and cratering events. Thus asteroids are unlike larger planets, whose outer layers are modified and contaminated by cratering. Unmodified asteroidal rocks are revealed as the outer layers are stripped away. Further, fragments of catastrophic collisions

reveal cross-sections of the deep interiors of precursor bodies.

- (4) At least one asteroid (Vesta) is covered by basalts, and several other asteroid types are believed to be composed of once-molten or highly metamorphosed, highly differentiated materials (e.g., the S-type class, probably of stony-iron composition, and the metallic M-type). These are the smallest objects in the solar system thought to have been melted and to have undergone planetary-type differentiation. Surprisingly, they co-exist in orbits similar to those of the majority of asteroids of primitive composition. Thus they strongly constrain the sources of heat in the early solar system.
- (5) Asteroid surfaces are composed of major mineral phases similar to those of many classes of meteorites (including carbonaceous and ordinary chondrites, basaltic and enstatite achondrites, and irons and stony irons). Collisional and dynamical processes can transfer fragments from some mainbelt asteroids into appropriate Earth-crossing orbits on time scales comparable to meteorite cosmic ray exposure ages. Thus in all probability the asteroids are the only objects other than the Earth and perhaps some comets from which we have actual samples. A vast quantity of data has been obtained from meteorites which tells us about the asteroidal parent-bodies.
- (6) Cratering was certainly the dominant geological process on all terrestrial planets prior to 4 billion years ago and remains so for the Moon and Mercury. The source of impacting bodies must be Sun-orbiting planetesimals, the only remnants of which today are the asteroids and comets. Thus the collisional and dynamical history of asteroids is critical to understanding early terrestrial planet geology.
- (7) The very last phase of planetary accretion may have been dominated by material originally located far from planetary orbits. Larger objects were gravitationally scattered by planets, and "dust" was redistributed by radiation processes. The chief source of this material may have been the last remaining population of planetesimals, especially one fragmenting and comminuting itself into dust. The asteroids are such a population. The degree to which surface compositions of terrestrial planets are contaminated or modified by asteroidal material depends on how much mass was originally in the asteroid belt and on the efficacy of the redistribution processes.

There are two perspectives on the nature of asteroids that differ from that outlined above. Although they are not widely accepted, they deserve mention because of their potential importance. (1) Some feel that, in the competition between accretion and fragmentation, accretion processes may be dominating over fragmentation in the asteroid belt

today, at least in certain places and for certain sizes. The prevailing view, however, is that while asteroids provide a window on the early accretion processes, net accretion is not an ongoing process which may be observed today. (2) A widely advertised hypothesis suggests that comets and asteroids may have resulted from the comparatively recent explosion of a large planet in the asteroid belt. The proponents of this revolutionary hypothesis have not yet addressed the many obvious incompatibilities with meteoritical and dynamical evidence.

SECTION IV

MAJOR SCIENCE OBJECTIVES FOR FUTURE EXPLORATION

As viewed from the perspective of 1977, the asteroids present us with the following major problems which have broad relevance to understanding the early evolution of the solar system and for understanding other terrestrial bodies in a comparative planetological framework.

- (1) What are the genetic relationships, if any, among the mainbelt asteroids, Apollo-Amor asteroids, Trojan asteroids, comets, small planetary satellites (e.g., Martian satellites, Jupiter's outer satellites), the meteorites, interplanetary dust, and interstellar dust? What are the characteristics of the present populations of small bodies? How are their orbits distributed in space and what are their size distributions? Are any asteroids cometary nuclei, perhaps still degassing? It is especially important to tie the meteorites to specific bodies in the asteroid belt or elsewhere. That will enable us to better understand the context of meteoritical evidence on chemical fractionations, agglomeration and accretion, thermal processes, remanent magnetism, early solar system chronology, impact processes and interactions with the space environment, the nature and distribution of primitive material, the early history of the Sun, and so on.
- (2) What was the composition of nebular condensates as a function of position in the early solar system? How well does the asteroid population, which now ranges from within 1 AU of the sun to beyond 5 AU, reflect the original distribution of material? What kind of dynamical mixing has taken place? Is the asteroid belt a dumping-ground for a substantial amount of material formed in faraway parts of the solar system? It is known from studies of oxygen isotopes that the meteorites sample half-a-dozen distinct parts of the solar nebula that have never been thoroughly mixed since nucleosynthesis; are these materials now, and have they always been, confined to the relatively small volume of the asteroid belt? Or are the asteroids that seem to have the same major mineralogical phases as the different meteorite classes actually of different isotopic compositions? Is there evidence of temperature, pressure, or compositional gradients through the asteroid belt as a function of distance from the Sun or distance above the median plane? What was the nature of any prebiologic environments in the outer parts of the asteroid belt where there may have been water-rich and carbon-rich materials?
- (3) Do the asteroids represent a tableau of the early processes of accretion? How much mass was originally in the asteroidal zone? Why did a planet fail to accrete in the belt? For how long were asteroids accreting before fragmentation began to

dominate? What process (e.g., Jupiter perturbations?) stopped accretion? What do the cross-sectional layers in fragmental asteroids reveal about accretion (in petrographic textures, distribution of "chondrules", and regolith-like characteristics)? To what degree does the interaction of asteroids with the present small-particle population shed light on processes of accretion/fragmentation?

- (4) Why has the thermal evolution of various asteroids differed? What was the source of heating and when did it happen? What is the smallest body that was substantially heated? Did the thermal evolution of Vesta as a differentiated planet evolve as far as the Moon, or farther? How pristine and unaffected by the heating processes are the primitive asteroids? What does the asteroidal evidence say about the initial thermal states of other planets? What can be learned about processes of geochemical segregation from examination of layering within fragments of differentiated precursors, and from direct examination of remnant metallic cores, if they exist? Have objects followed different evolutionary paths because of differences in size, differences in initial conductivity, different distances from the Sun, different abundances of short-lived and/or long-lived radioisotopes, different collisional histories, or other reasons? Was the heating which melted at least the surface of Vesta generated within the body or imposed from the outside?
- (5) To what degree has asteroid collisional and dynamical evolution affected the terrestrial planets? What are the sources of the populations of impacting bodies that cratered the Moon, Earth, Mercury, Venus, Mars, Phobos, etc.? How has the cratering flux changed with time? How precisely can we use crater densities for the interplanetary correlation of geologic time? What has been the role of resonances in feeding asteroidal fragments into planet-crossing orbits? To what extent has the comminution and redistribution of asteroidal dust affected the composition of the surface layers of terrestrial planets?
- (6) What is the potential of the asteroid population as a source of raw materials? What materials of economic value are concentrated in the different types of asteroids? Are asteroids in the most accessible orbits composed of valuable materials? (This area is a question of applied science. If the answers are positive, the potential economic return from exploration of the asteroids will have a major effect on how that exploration is carried out.)

SECTION V

REQUIRED MEASUREMENTS FOR POTENTIAL MISSIONS

Close encounters between spacecraft and asteroids are required for the following kinds of observations: (1) significant spatial resolution of structure or composition; (2) measurement of mass, hence density; (3) measurement of magnetic fields (which may well be present since meteorites exhibit remanent magnetism); (4) remote-sensing techniques which require proximity or large subtended solid-angle (e.g., γ -ray or X-ray fluorescence spectrometry); (5) measurements requiring contact with the object; and (6) sample measurements requiring specific knowledge of exactly where the sample came from (it will always be a matter of some conjecture as to which asteroids are the parent-bodies for specific meteorites, and certainly we can never be sure from where on a specific asteroid a particular meteorite came).

Asteroids are a widely distributed population of dissimilar bodies, and the principal science objectives require an understanding of the ensemble of asteroids. It is thus essential that several asteroids be investigated in some detail. A mission must study a typical S-type (silicaceous or stony iron) asteroid, a typical C-type (carbonaceous) asteroid, and Vesta; every effort should be made to measure Ceres and a few other objects, as well. Thus a multiple-asteroid mission involving a minimum of four objects, and preferably six or more, is required.

All of the following measurements are important; some are essential:

- (1) Determination of masses to 1% or better in order to yield densities. These can be measured from the Earth for only about three asteroids and with poor precision (10%). Also important are measurements of the gravity field that are sufficiently sensitive to detect major inhomogeneities (such as those due to hunks of iron in a "raisin-bread" asteroid model).
- (2) Imaging capability, with resolution of better than 100 meters, in order to measure asteroid shapes, crater populations, and other morphological and structural features.
- (3) A magnetometer, to study any remanent magnetic fields (meteorites show remanent magnetism). This and other cruise-science instrumentation can examine the interplanetary and interasteroidal space environment and study interactions between asteroids and their environment.
- (4) Adequate elemental chemical measurements of whole asteroids (spatial resolution not necessary) that would chemically distinguish major meteorite types from each other.
- (5) Spectral measurements of sufficient spectral resolution to identify major mineralogical assemblages and with some spatial

resolution for identifying mineralogical phases and their spatial variations. Spatial resolution on Vesta is especially important and should not be poorer than 30 x 30 resolution elements.

Other capabilities, including radiometry and photometry, would also be useful. Less well understood are advantages that might accrue from direct contact with one or more asteroids. Short of the obvious advantages of sample returns, which we do not consider plausible for the pre-1990 time frame, a number of investigations could be made from penetrators, hard landers, or soft landers. The utility of geophysical measurements (e.g., heat flow, active seismometry, astrometry) should be evaluated in addition to the augmented advantages of landing for compositional and imaging purposes.

SECTION VI

MISSION CONCEPTS

As stated above, multiple-asteroid targetting seems to be the only viable concept for an asteroid-intensive mission. Using Venus-Earth gravity-assist trajectories, it has already been demonstrated that ballistic trajectories that encounter up to a half-dozen asteroids are easy to find. The difficulty with such a mission is that staytimes are very short at typical encounter velocities of 5 km sec^{-1} or more. At such velocities, very preliminary analyses suggest that crude geochemical measurements could be made of only the largest asteroids. Other experiments will also be seriously impeded by short staytimes, especially for asteroids other than Ceres, Pallas, and Vesta. Nevertheless, there has been no detailed study of how seriously these measurements are compromised in a ballistic flyby mode, and some effort should be made to study the problem if low-thrust propulsion capabilities are not realizable.

Our preliminary considerations suggest that the only viable multiple asteroid mission is one which involves encounter velocities $< 1 \text{ km sec}^{-1}$ and preferably much lower-velocity rendezvous with several targets. These requirements can be achieved only by low-thrust propulsion systems such as ion drive or solar sail. We therefore recommend that a low-thrust multiple-asteroid rendezvous (or slow flyby) mission be accomplished as soon as feasible. The development of the ion drive or solar sail would delay such a mission to about 1984 at the earliest. The mission should encounter Vesta, an S-type, a C-type, and preferably Ceres, and other objects of opportunity that display a variety of orbital and physical characteristics. The spacecraft should carry instrumentation adequate to make the measurements specified above.

Very brief studies of possible mission scenarios have been made for both ion drive and solar sail propulsion systems in the mid-80's, but the range of additional target opportunities is yet to be explored. There appear to be many mission candidates that will satisfy the science objectives. Unfortunately, however, there has been no advanced mission analysis, even in moderate detail, for missions of this type. We strongly recommend that the optimum mission be identified and that it be studied in detail immediately so that it may be more properly evaluated and placed in its proper position in the NASA mission model. While we are confident that a sound mission can be developed, such detailed examination is necessary before we can adequately evaluate its priority with respect to other planetary missions and the degree to which it can supersede ground-based research.

Specific questions which should be addressed by such a study include the following:

- (1) How many multiple asteroid rendezvous stopovers can be achieved with a plausible low-thrust system? or must some of the multiple asteroid encounters be in the slow flyby mode?

- (2) What are the targets available? Is it possible to find a multiple-asteroid mission that encounters Vesta and Ceres, in addition to the suite of other asteroid types desired? In the past, only certain examples of trajectories have been calculated, but we now require a comprehensive summary of the possibilities. What is the duration of such a mission and what range of target orbital parameters can be surveyed?
- (3) What are the limitations of various standard or state-of-the-art instruments in measuring asteroids of different sizes at plausible slow flyby velocities? Can all the requirements specified above be met (for γ -ray, X-ray, imaging devices, mass determination, and other experiments)?
- (4) What is the potential for contact with one or more asteroids, either by soft or hard landings? What additional science can be done by such contact and is it worth slowing down to a stop to do it? Can hard landers be deployed usefully and can they communicate their measurements to Earth?

SECTION VII

SR&T REQUIREMENTS AND OTHER STUDIES

We have identified the immediate need for developing scenarios for low-thrust, multiple-asteroid rendezvous missions in the mid-80's. Pending confirmation of preliminary indications that ballistic flybys do not permit adequate measurements to be made, we regard the development of a low-thrust propulsion system as essential to a viable asteroid mission. We point out the great utility such a propulsion system has for other terrestrial bodies missions.

The burden for asteroid studies will remain for some time on Earth-based approaches: (1) direct astronomical measurements using an array of existing techniques from the ground, and later from the Space Telescope; (2) laboratory investigations of meteorites, which are presumed asteroid, and perhaps cometary, fragments; and (3) theoretical investigations of celestial dynamics cosmochemistry, and other areas that bear on the physics and evolution of small bodies. These approaches continue to bear fruit and should be maintained; their funding should not be tied to an early mission because in many ways they serve as useful alternatives to an early mission.

Present ground-based optical and infrared techniques have yielded the following kinds of information about dozens to hundreds of asteroids: diameter and shape, albedo, spin-period, compositional group (C-, S-, M-, E-types, etc.), and presence of pyroxene, olivine, metallic iron, and opaques. Such observations could eventually be extended to nearly 1000 objects. More refined optical and infrared techniques, combined with ground-based radar, have yielded more specific information for a few asteroids, including orientation of the spin vector; albedo variations; fayalite/forsterite proportions of olivine; enstatite/Fs proportions of orthopyroxene; thermal inertia; radar electrical properties; and indications of surface roughness and texture. These studies could eventually be extended to a few hundred objects, given an expanded ground-based program. Observations from Space Telescope could yield crude maps of some of the larger asteroids, more refined compositional inferences (particularly for organic materials) and some further improvement over ground-based techniques.

Preliminary studies suggest that serendipitous close passages to asteroids by spacecraft traversing the asteroid belt are very unusual. Should such an opportunity present itself, useful measurements can certainly be made and every effort should be made to capitalize on the opportunity. On the other hand, such fast flybys of a single asteroid cannot achieve most of the required objectives we have identified. Existing missions should thus not be seriously compromised to achieve such an encounter, nor does it make good sense to plan a future mission in a way that involves only a single asteroid fast flyby.

SECTION VIII

SUMMARY RECOMMENDATIONS

TBSWG recommends a multiple-asteroid rendezvous mission for the mid-80's, following the development of a suitable low-thrust propulsion device (e.g., solar sail or ion drive). We cannot propose a specific mission now inasmuch as no detailed mission scenario has been developed, but it is known that there are numerous multi-asteroid opportunities available in any particular year.

Therefore, in view of the significance of asteroids and meteorites to understanding the origin and early history of the solar system and the topography of the terrestrial bodies, TBSWG recommends that:

- (1) Advanced mission studies should begin now to develop a viable multiple-asteroid rendezvous mission and determine the degree to which it will answer fundamental questions.
- (2) A multi-asteroid rendezvous mission be maintained in the NASA mission model for the post-1984 time frame, pending the development of low-thrust propulsion and completion of the mission studies recommended above.
- (3) A vigorous ground-based program of asteroid observation must continue, using optical, thermal IR, and radar techniques.
- (4) A broad program of meteorite research should be developed in order to capitalize on the experimental techniques perfected in lunar sample analysis by applying them to the wide variety of extraterrestrial samples in our meteorite collections.
- (5) A sustained theoretical effort is required to understand the processes that have affected the asteroids and meteorite parent-bodies and to relate them to questions concerning solar system origin and planetary evolution.